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Nylon Tent Screens Out Smoke Particulate Matter

A. David Blakely

Abstract—A nylon tent designed for firefighters was placed in a smoky environment in a wind tunnel. The close knit fabric screened out 95 percent of the particulate matter but none of the gases in the smoke. There was no oxygen depletion in the tent when a person was in or out even though smoke concentrations were higher than normally encountered in fire camp situations.

Keywords: firefighters, toxic emissions, sleeping quarters

In recent years fire managers have expressed concern for the health of wildland firefighters because of their increasing numbers seeking medical relief from effects of exposures to smoke from burning vegetation on several large fires (Ward and others 1989). Analysis of the problems by medical research reveals that health-related effects caused by some types of exposure can be minimized or avoided if personnel with healthy metabolisms are periodically allowed to breath air containing little or no pollutant concentrations long enough for their systems to detoxify (American Conference of Governmental Industrial Hygienists 1992-93).

Smoke from burning vegetation consists of gases, volatile organic compounds, particulate matter, and an array of other compounds. Wildland fires produce some of these pollutants in sufficient quantities to affect the physical well-being of firefighters who are exposed to high concentrations for short periods or moderate concentrations for long periods (Dost 1991; Ward 1989).

Currently, we do not know specifically what the long-term effects of smoke exposure may be, but we recognize some doses make firefighters feel poorly and directly affect their health, safety, and work capabilities. Some of the toxicants and pollutants contained in vegetation smoke are listed in appendix A. Also listed are Occupational Safety and Health Administration permissible exposure limits and American Conference of Governmental Industrial Hygienists time weighted average/threshold limit values for industry.

One way to give firefighters a break from breathing polluted air and reduce the subsequent distress is to isolate them from smoky environments during rest and sleeping periods while assigned to a fire. Because of the logistics of moving large numbers of firefighters long distances, in many fire situations it would be impractical to transport the firefighters to smoke-free environments. In fire camp situations, making onsite air completely free of pollutants would require enclosed facilities that have powered ventilation and filtering systems that cleanse the air. On remote wildland fires, such facilities could be expensive and impractical, especially if totally smoke-free air is not mandatory to protect firefighter well-being and maintain optimum work productivity. Therefore, one suggestion is that firefighters sleep in individual or group tents that screen out most of the particulate matter, thereby eliminating the need for special pumps or filtering systems.

When a tent is set up in a smoky area, the initial volume of air in the tent will be filled with smoke unless some mechanical means has been used to recycle and filter it. Otherwise, particulate matter in the tent will be slowly removed from the air as it is breathed in and out of the occupant's pulmonary tract (nasal, trachea, bronchia, and lungs). As the initial volume is inspired and the tent remains closed, most of the particulate matter will be removed from new air as it enters the tent via gaps between fabric strands, but probably none of the polluting gases will be removed. Most of the larger particles will be kept out by the tightly woven fabric, while some of the small particles

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A. David Blakely is Research Forester, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, located at the Intermountain Fire Sciences Laboratory, Missoula, MT.

will penetrate and be inspired by the occupant. Even though some small particles get through to the occupant, they will stick harmlessly in the upper respiratory tract because many large particles will no longer be present to cover surfaces (protected by mucosa and cilia) that naturally intercept and eject foreign matter (Brief 1975; Martonen 1992). On this basis the tent filtering capabilities should offer an advantage and some relief.

When a nonvented tent is occupied by a firefighter for several hours, questions arise about the effects of the outside smoke concentrations on the atmosphere inside. Some of the unknowns are:

1. How much of the particulate matter can be kept out by a specific tent fabric?
2. Is there a significant oxygen depletion (reduced to below 19.5 percent)?
3. Are the outside polluting gases or volatile organic compounds kept out by the tent fabric?
4. Does normal breathing inside the tent cause an increase in CO_2 concentration?
5. Do pollutant ratios inside the tent change when smoke concentration changes outside the tent?

These questions are asked because adverse effects can contribute to the degradation of firefighter health and work capabilities. For example, if by some means a buildup of CO occurs in an occupied tent, the result would be increased carboxyhemoglobin in the firefighter's blood and less oxygen transported to the brain, heart, and other muscles. A large enough blood oxygen depletion would cause sickness and diminished ability to think or work, or the headache that might occur (Countryman 1971; Kaplan and Hartzell 1989).

If oxygen is reduced because of high CO_2 concentrations caused by normal breathing, it would also cause headaches and reduced abilities to think and work. Answers to questions about particulate matter, volatile organic compounds, and gases are important for judging the value of using a closed shelter versus firefighters sleeping in the open where they might be exposed to a high concentration smoky atmosphere.

This study was performed to determine how much particulate matter and pollutant gas will penetrate a tent, specially designed for firefighters, when the tent is set up in a moderate smoke concentration environment. The small nylon tent used in this study was designed and built by the Forest Service, U.S. Department of Agriculture, at the Missoula Technology and Development Center with new experimental fabric (described in appendix B). The total air volume in the tent was calculated at 1,612 L. A person at rest and breathing 10 L per minute would breath this volume of air in about 2 hours and 41 minutes. Theoretically, after about 3 hours all the air in the tent would be filtered at least once by a person's pulmonary system (if the exchange with outside air through the tent fabric is ignored).

METHODS

The tent was placed on a low table in the large wind tunnel at the Intermountain Fire Sciences Laboratory. For experimental purposes a large hole was cut in the tent side and a see-through plastic window and two plastic gloves were mounted and sealed into it. The gloves were used to access the inside of the tent when no one was inside to operate air sampling equipment and to access equipment outside the tent when someone was in the tent and attending equipment on the outside. This system allowed work without opening the zippered tent doors and letting in unwanted smoke.

Pumps, filter cassettes, data loggers, gas detectors, and other support equipment were arranged in the tent for convenient access. A cord was placed along the inside top of the tent so that sensors and filter cassettes were suspended above the floor in the approximate breathing zone of a reclining firefighter.

Fires with either 1 or 0.5 kg of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) needles were allowed to burn freely to fill the tunnel with smoke (approximately 286 m^3 in volume when the inlet and outlet doors were closed). For three fires, small amounts of water were added to the fuel to generate higher levels of particulate matter. Fuel moisture content was not measured because the water was added only to cause an unspecified increase in the amount of particulate matter. A fan was used in the tunnel to circulate and mix the air and smoke. The concentration of smoke and combustion efficiency was not controlled (other than by weight of fuel) because the intent was to produce a smoky atmosphere that would surround and penetrate the tent fabric. The fuel moisture content of dry fuel was between 5 and 7 percent, and the relative humidity in the wind tunnel was approximately 30 percent.

Three tent arrangements were used to determine what and how much the tent screened from the surrounding smoke. By making simultaneous measurements inside and outside the tent, screening and gas scrubbing properties were determined.

Arrangement 1—The tent was zippered shut with the instruments inside **before** smoke generation was started. The instruments and filters inside the tent measured the amount of particulate matter and the gas concentrations that penetrated the tent fabric and mixed with unpolluted air inside.

Arrangement 2—The instruments were placed inside the tent and the door flaps were zippered shut **after** the tent filled with smoke and CO concentration reached the approximate maximum. The instruments inside measured the particulate matter and gases as the atmosphere inside the tent was continually filtered by pump-filter combinations. Other gases were monitored to determine their concentrations in and outside the tent (CO_2, formaldehyde, acetic acid, and formic acid). This method simulated a tent set up in a smoky environment and the firefighter entering and remaining inside the closed tent to sleep. The pumps and filters continued to recirculate the air in the tent and filter it more than once, not unlike what a person's pulmonary tract would do in a closed tent.

Arrangement 3—A person entered the tent **after** it filled with smoke, and then the tent was zippered shut. This part of the study was designed to measure amounts of particulate matter that were filtered from the air inside the tent by the occupant's pulmonary tract and to determine if there were any gas concentration increases caused by a person's breathing. The person's lungs filtered about 10 or 12 L per minute during normal breathing while resting. The glass fiber filters alone removed almost all the particulate matter, but the human pulmonary tract "filtered" only part of the particulate matter. Experiments have shown that some of the smaller (less than 0.2 µm) particulate matter may be breathed into the pulmonary tract but is then exhaled to mix with the free air to be breathed again in later inhalations (Brief 1975). This test (with a human subject) was conducted because the other tests with filters and pumps remove almost all the particulate matter and put little back into the tent.

EMISSIONS DETECTION EQUIPMENT

The equipment included filtering systems and various measuring devices.

Particulate Matter Filtering Systems

Filters used to collect particulate matter were 37 mm in diameter and made of glass fiber (Millipore type AP 1.0 micron). They were preconditioned to a constant weight (70 °F and 35 percent relative humidity), weighed, subjected to smoke (in conditions of approximately 70 °F and 30 percent relative humidity) for periods from 15 to 65 minutes, then reconditioned for 1 hour and weighed again. Aluminum cyclones were placed on plastic filter cassettes to separate particles by size classes. When constant flow air pumps (model Alpha-1 made by E. I. du Pont) were set for 2 L per minute flow rates, the cyclones were designed to have a cut point of 2.5 µm diameter particulate matter.

For total particulate matter tests, a filter was used in conjunction with each gas detector tube for the entire time (about 1 hour). Cyclones were used to capture particulate matter 2.5 µm, and filters without cyclones collected total particulate matter. On other tests, filters were changed more often (15- or 30-minute intervals) so the particulate matter during different smoke concentrations could be determined. For the test with a human in the tent, the filters were changed every 15 minutes so data could be more accurately correlated with the CO concentrations recorded by the data loggers.

Airflow Measurement

A bubble flowmeter (Gilibrator made by Gilian) was used to measure the flow rates for calculating the air volumes pumped through the filters and color detector tubes. The flow rates were measured after each filter change. Filter pumps placed inside the tent had both intake and exhaust ports vented inside the tent so the air would not be forced through the tent fabric either by low pressure or partial vacuum. Pumps were run at rates from 0.5 to 2 L per minute.

Gas Emissions Detector Tubes

Chemical detector tubes (described in appendix A) were placed between the filters and the constant flow pumps to measure the concentrations of formaldehyde, formic acid, acetic acid, CO_2, and CO. Carbon monoxide diffusion tubes (color detector tubes that are passive monitors and do not need air pumped through them) were placed inside and outside the tent to make comparisons to the CO data logger concentrations. An electro-chemical oxygen detector (Exotox 55 made by Neotronics) was placed inside the tent to measure oxygen depletion occurring during the fires and while a person was in the tent.

For tests performed to determine only gas concentrations in and out of the tent, pumps, filters, and detector tubes were placed outside the wind tunnel chamber. Teflon tubes (5 mm inside diameter) delivered the smoke samples through ports in the wind tunnel walls to the pumps and back to the tent after they had passed through the filters, detector tubes, and pumps. Returning the filtered samples to the tent prevented a partial vacuum in the tent that could have pulled smoke into it. This arrangement allowed the detector tubes to be read periodically and changed and flow rates to be measured without someone having to be inside the smoke-filled tunnel.

Carbon Monoxide Detector

Electro-chemical CO detectors/data loggers (National Drager 190) were placed inside the tent to measure the CO concentration changes as the smoke inside the tent was filtered and recycled. CO detectors were placed outside the tent to record the changes in concentrations as the fuels flamed and smoldered and smoke filled the sealed tunnel. The gas concentrations were sampled each second and gave a readout of time weighted average, peak, and current concentrations (tables 1 and 2)

Table 1—Carbon monoxide inside tent (human inside tent)

Elapsed time in minutes, hours	Parts per million									
	0	1	2	3	4	5	6	7	8	9
0:00	0	0	0	0	0	24	29	42	47	50
0:10	59	59	62	66	69	69	69	69	68	68
0:20	68	68	67	67	67	67	66	66	65	65
0:30	64	63	63	62	61	61	60	59	58	57
0:40	56	55	54	53	52	52	51	50	49	48
0:50	47	46	45	44	43	43	42	41	40	39
1:00	38	38	37	36	35	35	34	33	32	32
1:10	31	30	29	29	28	27	27	26	26	25
1:20	24	24	23	22	22	22	21	21	20	20
1:30	19	19	18	18	18	17	17	16	16	15
1:40	15	14	14	14	13	13	12	12	12	12
1:50	11	11	11	10	10	10	10	9	9	9
2:00	8	8	8	8	7	7	7	7	6	6
2:10	6	6	6	5	5	5	5	5	7	10
2:20	16	22	27	34	40	46	49	52	55	57
2:30	58	60	61	61	62	62	62	62	62	62
2:40	61	61	60	60	59	58	58	57	56	56
2:50	55	54	53	52	51	50	49	48	48	47
3:00	46	45	45	44	43	42	41	40	39	39
3:10	38	37	36	35	35	34	33	33	32	32
3:20	31	30	29	28	28	27	26	26	25	24
3:30	24	23	23	22	22	21	21	20	20	19
3:40	19	18	18	17	17	16	16	16	16	15
3:50	15	14	14	14	13	13	13	12	12	12
4:00	12	11	11	11	10	10	10	10	9	9
4:10	9	8	8	8	8	8	7	7	7	7
4:20	7	7	6	6	6	6	6	5	5	5
4:30	5	5	5	4	4	4	4	4	4	4
4:40	4	4	4	3	3	3	3	3	2	2
4:50	0	0	0	0	0	0	0	0	0	0

throughout the experiment. A data logger software program was used to compute the time weighted averages and construct tables and graphs of the data for each fire.

RESULTS

Figure 1 and tables 3 through 6 show data from two fires, one with a human inside and the other with no one in the tent. For both fires the particulate matter outside the tent increased to a high level then decreased because of a combination of factors including chamber doors leaking, particulate matter settling out, and gases probably reacting with each other and the walls of the wind tunnel. When a second smoke source was started, the particulate matter outside the tent quickly increased again. As the particulate matter levels outside the tent increased and decreased, the particulate matter concentration inside was decreasing but at a rate determined by the volume of air passing through the glass fiber filters and the human's pulmonary system (shown in tables 3 through 6). The particulate matter level inside the tent decreased at the filtering rate and showed no relation to the smoke concentration changes occurring outside. Figure 1 shows an estimate of the decreasing particulate matter level calculated using the measured volume removed solely by the filters. There was no change in the O_2 concentration while a person was in the tent.

Levels of particulate matter that were measured inside and outside the tent during several other fires are listed in table 7. Substantial reductions in particulate matter and particulate matter 2.5 inside the tent were measured. Listed are the fractional comparisons of (1) particulate matter in and out of the tent, (2) particulate matter 2.5 in and out of the tent, and (3) particulate matter 2.5 collected inside the tent compared to total particulate matter collected outside the tent. The screening efficiency of the tent fabric was high, averaging about 94 percent reductions from outside to inside concentrations. When water was added to increase the total particulate matter, the fraction that penetrated the tent fabric was almost the same as for the drier fuel fires. The particulate matter collected

Table 2—Carbon monoxide outside tent

Elapsed time in minutes, hours	Parts per million									
	0	1	2	3	4	5	6	7	8	9
0:00	0	0	0	0	5	18	39	56	67	68
0:10	69	73	78	78	76	75	75	71	75	74
0:20	75	74	73	72	72	70	68	69	68	68
0:30	68	66	64	63	62	62	60	59	59	57
0:40	56	56	54	54	53	51	51	49	48	47
0:50	47	45	45	44	43	43	41	40	40	39
1:00	37	35	35	36	35	34	33	33	32	32
1:10	30	30	29	28	27	27	26	25	25	24
1:20	24	23	23	22	22	21	21	20	20	19
1:30	19	18	18	18	17	17	16	16	15	15
1:40	15	15	14	14	13	13	13	12	12	12
1:50	11	11	11	11	11	10	10	10	9	9
2:00	9	9	8	8	8	8	7	7	7	7
2:10	7	7	6	6	6	6	6	7	15	24
2:20	43	60	66	71	71	70	70	72	73	74
2:30	70	73	70	70	70	69	69	68	67	66
2:40	65	65	64	63	62	61	60	60	59	57
2:50	57	55	55	54	52	52	50	49	48	48
3:00	47	46	45	44	43	43	42	41	40	40
3:10	39	37	37	36	35	35	34	33	33	32
3:20	31	30	29	29	28	27	27	26	26	25
3:30	24	24	23	23	22	21	21	21	20	20
3:40	19	19	19	18	18	17	17	17	16	16
3:50	16	15	15	15	15	14	14	13	13	13
4:00	12	12	12	11	11	11	11	11	11	10
4:10	10	10	10	10	9	9	9	8	8	8
4:20	8	8	7	7	7	7	7	7	7	7
4:30	7	6	6	6	6	6	6	5	5	5
4:40	5	5	5	5	5	5	5	4	4	4
4:50	2	1	0	0	0	0	0	0	0	0

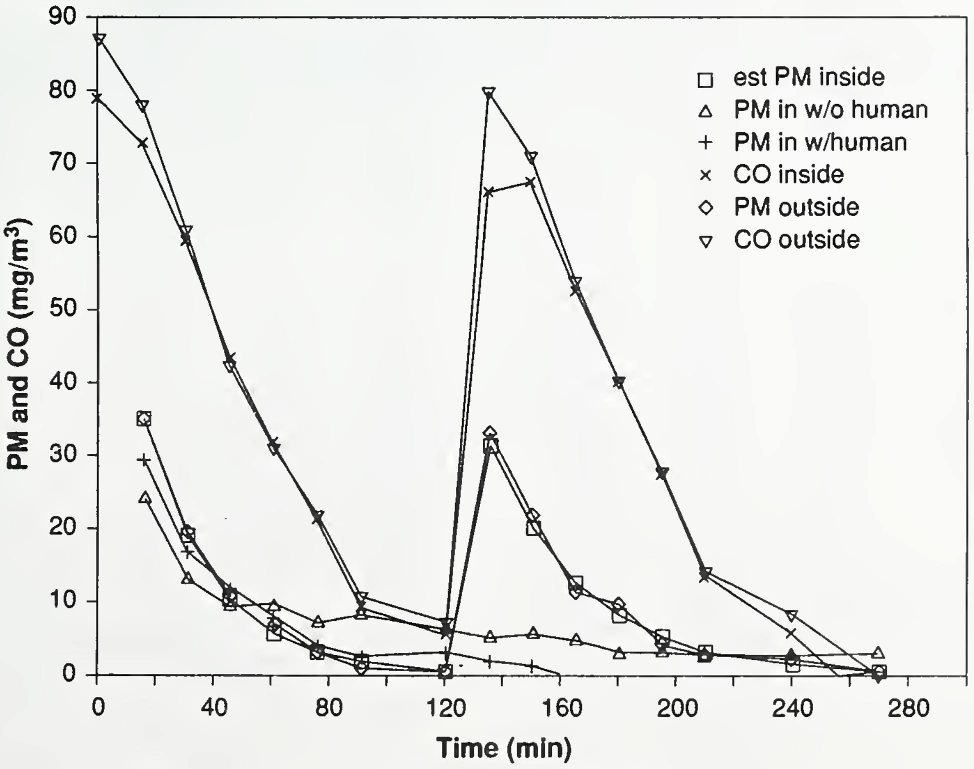

Figure 1—PM and CO from ponderosa pine smoke, with and without human in the tent.

Table 3—Particulate matter collected on filters without a person in the tent

Time	Samples					
	Outside tent			Inside tent		
elapsed	1-15	16-30	Avg[1]	31-45	46-60	Avg
Minutes			*mg/m³*			
			First fire			
15	18.57	15.48	17.82	24.46	24.31	24.39
30	9.43	8.16	8.80	12.36	14.38	13.37
45	4.53	2.92	3.73	8.93	10.65	9.79
60	2.06	0.79	1.42	7.28	11.68	9.48
75	[2]–0.27	2.18	0.96	5.40	9.37	7.38
90	–0.24	–0.29	–0.26	6.75	10.12	8.43
120	–0.22	–0.56	–0.39	6.46	7.00	6.73
			Second fire			
135	35.52	42.42	38.97	3.89	6.41	5.15
150	25.47	25.39	25.43	6.44	5.00	5.72
165	17.33	13.73	15.53	5.49	4.37	4.93
180	12.00	8.86	10.43	3.05	3.05	3.05
195	7.36	4.46	5.91	5.38	1.18	3.28
210	3.18	–0.50	1.34	2.56	2.86	2.71
240	1.89	–1.20	0.35	1.80	2.89	2.35
270	0.86	–1.54	–0.34	4.36	1.85	3.10

[1] Averaged samples were gathered concurrent and contiguous.

[2] Negative values reflect variation in weighing from balance and filter media moisture.

Table 4—Volume of air sampled through filter pumps without a person in the tent

Time	Inside tent		Fraction of	Outside tent	
elapsed	Avg	Accum.	tent vol.	Avg	Accum.
Minutes	*Liters*		*Percent*	*Liters*	
15	26.47		1.64	46.00	
30	25.89	52.37	3.25	47.00	93.00
45	25.77	78.14	4.85	48.00	141.00
60	25.62	103.76	6.44	49.15	190.15
75	25.55	129.30	8.02	50.00	240.15
90	25.59	154.89	9.61	50.78	290.93
120	51.09	205.98	12.78	81.40	372.33
135	24.86	230.84	14.32	52.93	425.25
150	24.80	255.63	15.86	54.15	479.40
165	24.83	280.46	17.40	55.30	534.70
180	24.60	305.06	18.92	56.35	591.05
195	24.66	329.72	20.45	57.45	648.50
210	24.68	354.39	21.98	58.15	706.65
240	49.71	404.10	25.07	90.23	796.88
270	49.71	453.81	28.15	91.44	888.32

Table 5—Particulate matter collected on filters with a person in the tent

Time	Samples					
	Outside tent			Inside tent		
elapsed	1-15	16-30	Avg[1]	31-45	46-60	Avg
Minutes			*mg/m³*			
			First fire			
15	35.39	34.31	34.85	26.62	31.77	29.19
30	21.07	17.44	19.26	13.81	19.87	16.84
45	11.88	9.85	10.87	10.11	12.78	11.44
60	7.83	5.85	6.84	7.29	7.91	7.60
75	4.40	2.33	3.37	2.95	5.02	3.98
90	1.56	0.18	0.87	2.50	1.41	1.95
120	1.46	[2]–0.09	0.69	2.95	2.72	2.83
			Second fire			
135	37.25	29.19	33.22	2.15	1.82	1.99
150	21.87	21.93	21.90	1.70	1.18	1.44
165	13.63	9.85	11.74	–0.68	–1.31	–0.99
180	9.14	9.89	9.51	–0.23	–1.05	–0.64
195	2.89	4.86	3.87	–0.23	–0.98	–0.60
210	1.88	4.30	3.09	–1.93	0.84	–0.54
240	1.72	2.03	1.88	–1.36	0.97	–0.20
270	0.73	0.30	0.51	0.68	0.19	0.44

[1] Averaged samples were gathered concurrent and contiguous.

[2] Negative values reflect variation in weighing from balance and filter media moisture.

Table 6—Volume of air sampled through filter pumps with a person in the tent

Time	Inside tent		Fraction of	Outside tent	
elapsed	Avg	Accum.	tent vol.	Avg	Accum.
Minutes	*Liters*		*Percent*	*Liters*	
15	24.59		1.53	46.66	
30	24.44	49.02	3.04	47.14	93.80
45	24.38	73.40	4.55	48.14	141.93
60	24.33	97.73	6.06	49.03	190.96
75	24.36	122.09	7.57	50.23	241.19
90	24.41	146.49	9.09	51.11	292.29
120	48.90	195.39	12.12	82.18	374.47
135	24.17	219.56	13.62	53.15	427.62
150	24.08	243.63	15.11	54.00	481.62
165	24.11	267.74	16.61	55.23	536.85
180	24.00	291.74	18.10	56.21	593.06
195	24.18	315.92	19.60	57.14	650.19
210	24.21	340.13	21.10	57.82	708.01
240	48.51	388.64	24.11	87.71	795.72
270	48.45	437.09	27.11	88.95	884.67

Table 7—Particulate matter concentrations in and out of the tent

	Filters				Fractions of PM and PM 2.5[2] filtered out by tent		
	Outside		Inside[1]				
Fire	With cyclone[3]	Open face	With cyclone	Open face	PM in/ PM out	PM 2.5 in/ PM 2.5 out	PM 2.5 in/ PM out
	mg/m³				*Percent*		
	Fires with 1.0 kg P-pine needles						
1	25.89	37.51	0.86	0.72	98.1	96.7	97.7
2	25.25	26.42	2.00	1.43	94.6	92.1	92.4
3	33.82	34.03	1.79	1.07	96.9	94.7	94.7
4	23.61	24.87	0.53	0.08	99.7	97.7	97.9
				Avg	97.3	95.3	95.7
				STD	1.9	2.2	2.3
	Fires with 0.5 kg P-pine needles						
5	4.83	5.02	0.40	0.20	96.1	91.8	92.1
6	19.36	20.07	0.78	0.61	97.0	96.0	96.1
7	23.80	25.23	1.80	1.26	95.0	92.4	92.9
8	11.00	10.89	0.91	0.58	94.7	91.7	91.6
9	7.95	8.16	0.45	0.46	94.4	94.3	94.5
10	7.95	8.16	0.27	0.41	95.0	96.6	96.7
11	9.08	8.48	0.60	0.77	90.9	93.4	93.0
12	9.08	8.48	1.08	0.42	95.1	88.1	87.2
13		11.4					
		10.8		1.3	88.7		
	Fires with 0.5 kg P-pine needles + 0.2 liters water added						
14		170.5					
		165.7		9.1	94.6		
15		101.1					
		125.7		3.9	96.6		
16		129.3					
		137.7		4.9	96.3		
				Avg	94.5	93.0	93.0
				STD	2.3	2.5	2.8

[1] Small differences between open and cyclone collected particulate matter inside the tent reflect errors from balance tolerances and filter media moisture.

[2] PM is total particulate matter collected on the filters. PM 2.5 is the particulate matter with a mean mass diameter of 2.5 µm that was collected on the filters.

[3] PM 2.5 is collected by filters fitted with cyclones.

for the 1-kg fuel fires was slightly higher than that collected for the 0.5-kg fires.

Table 8 shows gas data that were recorded from three fires. The gases detected were formaldehyde, formic acid, and acetic acid. Single samples of nitrogen dioxide and CO_2 were collected. Samples were taken inside and outside the tent to determine if there were gas buildups or depletions inside. Data in table 8 show that gas concentrations for the three fires were about the same inside the tent as they were outside.

On the three fires shown in table 8, CO:formaldehyde ratio averaged about 55 to 1, with the CO concentrations varying from 25 to 137 ppm. At this ratio and a threshold limit values/time weighted average ceiling of 0.3 ppm (value from American Conference of Governmental Industrial Hygienists; the Occupational Safety and Health Administration time weighted average is 1 ppm) for formaldehyde, the threshold limit values would have been exceeded when CO concentrations were above 17 ppm (55 ppm calculated for the Occupational Safety and Health Administration value). (The ceiling value is explained in appendix A.) The CO/acetic acid ratio averaged about 5 to 1, with the CO concentrations varying from 32 to 133. The time weighted average would be exceeded each time the CO concentration was above 50 ppm and the short-term exposure limit was above 75 ppm CO. CO/formic acid ratio averaged about 10 to 1. The 5/10 time weighted average/short-term exposure limit would be exceeded when the CO concentration was above 50 ppm and

Table 8—Ratio of CO to other gases in and out of the tent

	Concentrations[1]								
	Other gases					Carbon monoxide		Ratios	
			ACGIH	Do samples exceed					
Gas	Individual samples	Geometric mean	TWA/ STEL	TWA	STEL	Geometric mean	Individual samples	Geometric mean	Individual samples
	ppm					*ppm*			
				Fire 08101430					
Tent CH_2O	0.6	0.7	0.3 C	yes	yes	37	25	54	40
CH_2O	0.9			yes	yes		41		46
CH_2O	0.6			yes	yes		50		87
Tent acetic	9.9	9.9	10/15	no	no	51	51	5	5
CH_2O_2	2.2	2.3	5/10	no	no	34	23	15	11
CH_2O_2	2.4			no	no		50		20
				Fire 10101430					
Tent CO_2	3121		.5%/3%				36		<1
CH_2O	1.6	1.1	0.3 C	yes	yes	52	34	48	21
CH_2O	1.5			yes	yes		63		43
CH_2O	1.0			yes	yes		65		67
CH_2O	0.6			yes	yes		53		89
CH_2O_2	6.4	11.0	5/10	yes	no	54	34	5	5
CH_2O_2	13.4			yes	yes		63		5
CH_2O_2	16.7			yes	yes		65		4
Tent CH_2O_2	10.2			yes	yes		63		6
acetic	11.6	11.3	10/15	yes	no	52	53	5	5
Tent acetic	9.0			no	no		48		5
acetic	13.8			yes	no		55		4
				Fire 09101416					
CH_2O	1.0	1.8	0.3 C	yes	yes	100	47	55	47
CH_2O	2.6			yes	yes		128		49
CH_2O	3.4			yes	yes		137		41
CH_2O	1.3			yes	yes		120		95
acetic	7.8	12.9	10/15	no	no	76	32	6	4
acetic	15.5			yes	yes		105		7
acetic	17.9			yes	yes		131		7
CH_2O_2	16.8	16.8	5/10	yes	yes	133	133	8	8
NO_2	0.3	0.3	3/5	no	no		132	456	456

[1] CH_2O—formaldehyde; acetic—acetic acid; CH_2O_2—formic acid; TWA—time weighted average; STEL—short-term exposure limit; ACGIH lists no TWA or STEL for formaldehyde; C is ceiling—the concentration that should never be exceeded.

100 ppm CO, respectively. All gas in and out ratios were nearly constant regardless of the smoke concentration changes.

CONCLUSIONS

The changing CO concentrations inside the tent differed from the particulate matter concentrations in that the CO decreased and increased parallel to changes outside the tent. The only difference was that the inside concentration did not peak as high as that outside the tent. The difference was caused by the time for the CO to penetrate the tent fabric and migrate to the gas sensors. Because we do not expect any interference by the fabric, the cause of the delay must be because of the mixing of the gases at the fabric and internal volume interface. Inside the tent there was little movement of the gases or convective mixing. Therefore, the ends of the sampling tubes were not always in the most homogenous mixtures. The air and smoke in the chamber was constantly being mixed by a fan that operated during the entire sampling period. Because the detectors were placed in the center of the tent, the distance the CO had to travel to the detectors was the determining factor for the delay in detected concentration increase and decrease.

As shown in figure 1, the concentrations of CO both outside and inside the tent decreased at the same rate. The same mechanism for CO concentration changes can be expected to achieve equilibrium for any gases that are inside or outside the tent. Therefore, CO_2 produced inside the tent by someone breathing will not significantly increase, and other gas concentrations will not increase above what is outside the tent because of the diffusion through the tent and gas equilibrium constants (American Industrial Hygiene Association 1989).

This study shows that an average of 94.5 percent of the total particulate matter in the smoke was prevented from entering the tent by the close-knit nylon fabric, but the gases (CO, CO_2, formaldehyde, organic acids, and so forth) freely permeated the tent. Using this data and a particulate matter concentration of 1 mg/m^3 for a theoretical smoke concentration that might accompany a temperature inversion at a fire camp site, a resting firefighter (breathing about 10 L per minute for 8 hours) would inspire about 4.8 mg of particulate matter if sleeping in the open. If this same firefighter had been in the test tent, only 0.26 mg of particulate matter would have been inspired, about 18 times less. Removal of particulate matter also decreases dosages of many other pollutants that are adsorbed to the surface of particulate matter. Some of these are polycyclic aromatic hydrocarbons (benzo-A-pyrene) and semivolatile compounds (organic acids and aldehydes) that pyrolize as vapors in the fire and then condense on particulate matter. Benzo-A-pyrene is a known carcinogen when in high enough concentration, and organic acids and aldehydes are strong irritants to eyes and the nasio-pulmonary tract.

Predicted Weight Inconsistencies

A questionable difference is apparent in table 7 between the weights of open-faced filters and filters with cyclones attached. Most of the particulate mass on filters with cyclones was slightly more (average 0.3 mg/m^3) than what was on the open-face filters inside the tent. All reasonable logic says this difference should not exist. One explanation is that loss of fibers and uneven media drying results in large variation when weighing particulate at less than 2 mg. The mass of particulate matter and particulate matter 2.5 on filters outside the tent also showed differences about the same (average 0.4 mg/m^3) as those inside the tent, although those outside the tent had much larger accumulations. Despite the large variations, the most important factor is that the nylon fabric in the tent screened out more than 90 percent of the particulate matter, regardless of any shortcomings in the weighing methods or techniques.

More Studies Necessary

There is only speculation about which smoke component or combination of components may be causing the most serious health problems for firefighters. More study is needed to determine if staying in a tent for several hours will significantly decrease the effects of smoke exposure. Many toxicological studies have been made with primates and rats (Hartzell 1989) to determine the effects of high toxic gas concentrations. Using the tent, low to moderate concentrations need to be tested on people in controlled or precisely monitored smoke environments to determine what dose responses will result.

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APPENDIX A: CHEMICAL DETECTOR TUBES

The following color detector tubes were used to measure the concentrations of gases in the vegetation smoke.

Chemical tube	Chemical formula	Measuring range	TWA/STEL ACGIH[1]	TWA/STEL OSHA[2]
		ppm		
Acetic acid	CH_3-COOH	5 to 80	10/15	10/—
Carbon dioxide	CO_2	0 to 6%	0.5/3%	1/3%
Carbon monoxide	CO	10 to 300	25/—	35/200 C
Formaldehyde	HCHO	0.2 to 5	0.3 C[3]	1/2
Formic acid	HCOOH	1 to 15	5/10	5/—
Nitrogen dioxide	NO_2	0.5 to 10	3/5	—/1

[1] Time weighted average concentration/short-term exposure limit established by the American Conference of Governmental Industrial Hygienists.

[2] Time weighted average concentration/short-term exposure limit established by the Occupational Safety and Health Administration.

[3] A "C" designates a ceiling level that should never be exceeded.

Gas detector tubes are 6-mm by 110-mm glass tubes packed with chemical granules that change color when exposed to specific gases. Concentrations are determined by length of color stain and volume of gas passing through a tube. The measurement error of the different detector tubes is between 10 and 25 percent, and there are sometimes gases that interfere with the detection of the specified gas for a tube. The tubes are intended for a rough estimate of gas concentration and not for highly accurate measurements.

Note: The concentrations of gases in this table, other than CO and CO_2, cannot be relied on quantitatively because of the numerous interferences by other gases in smoke. The detector tubes were designed and manufactured to measure gases in atmospheres other than vegetation smoke. The tubes were used in this study only to determine what fractions of the gases produced outside the tent would penetrate the tent fabric.

APPENDIX B: TENT DESIGN

The tent, designed for one person, had a rectangular base, triangular front and back, and rectangular, sloping sides. It was 208 cm long, 102 cm high at the peak, and 152 cm wide at the base. The air volume inside the tent was calculated as approximately 1,612 L. Two fabric materials were used to construct the tent. The upper portions of the tent were constructed of 2.5 oz durable water-resistant nylon taffeta that measured an average 25.32 cfm permeability when air tested by engineers at the Missoula Technology and Development Center. The floor was constructed of 4-oz coated 250D polyester that indicated zero permeability when air tested. The test used a 4-mm orifice with test plate 34.5 cfm.

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